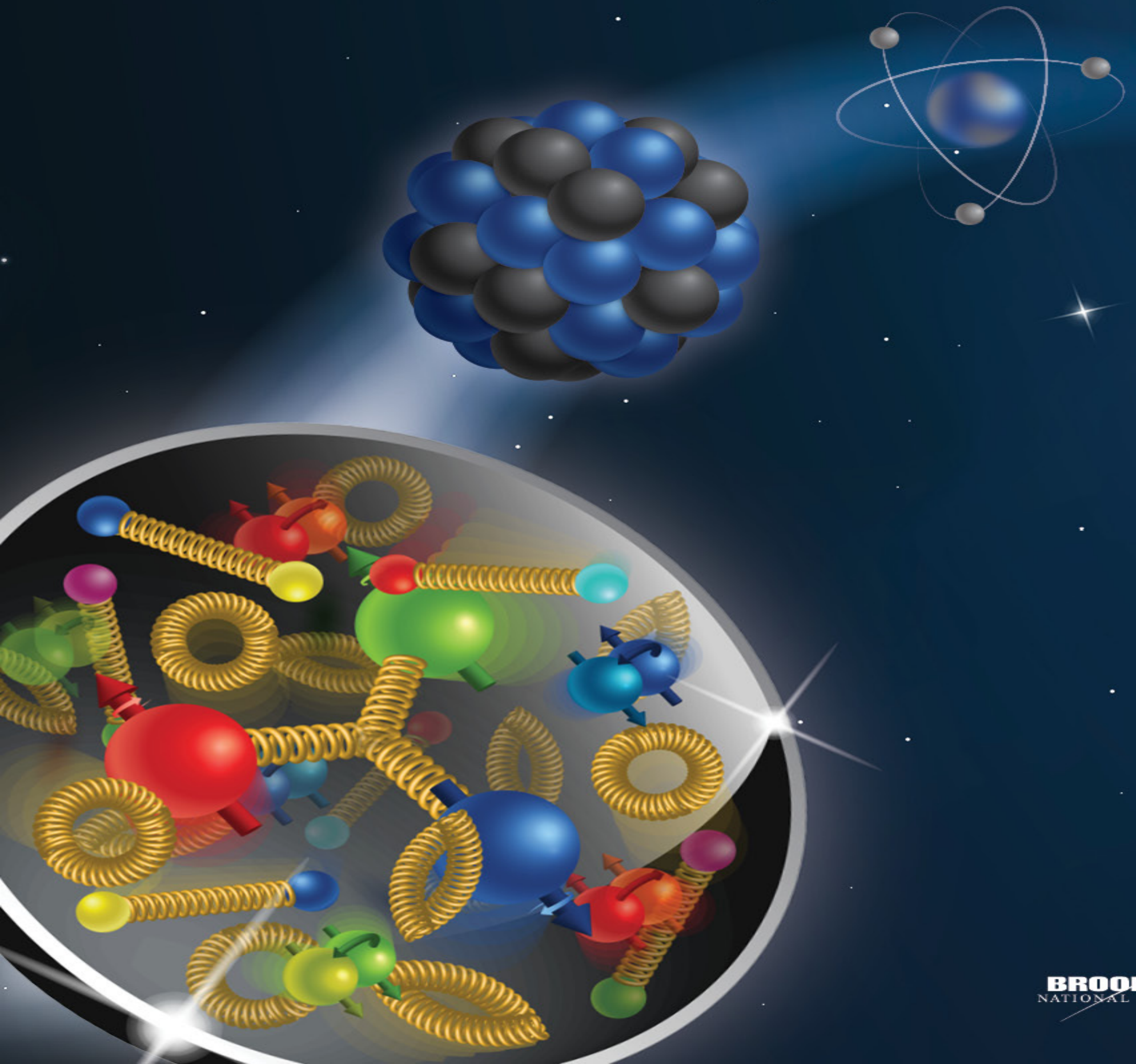


High Power RF Engineering -Cavity (3)

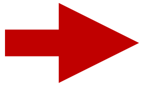
Binping Xiao

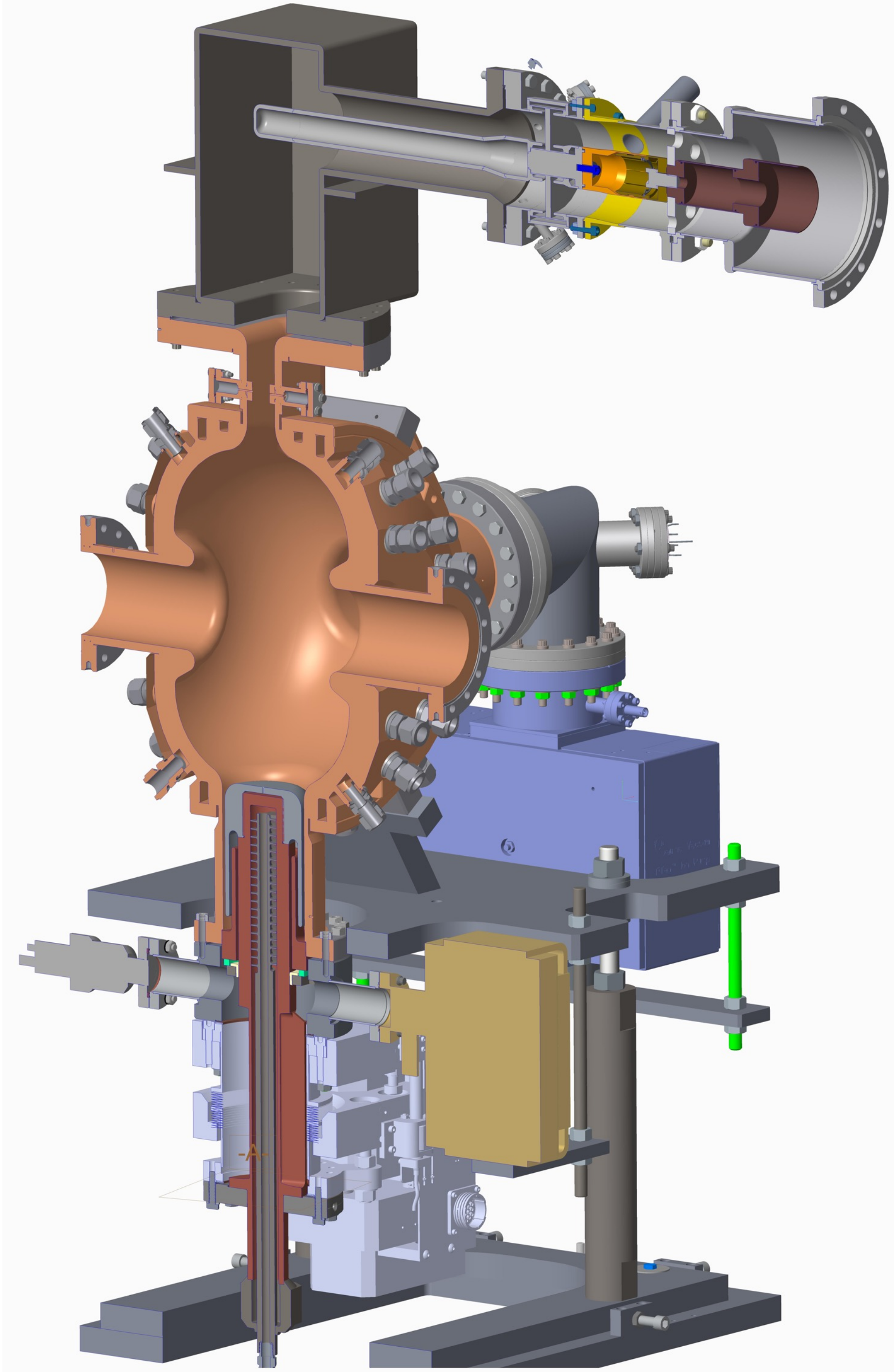
Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

RF cavities

Pillbox cavity





- Cavities need to be under vacuum since beam cannot go far in the air, need to add a beampipe to let beam go across the cavity.
- FPC, PU, frequency tuner, cooling channel, HOM damper, fundamental mode damper, vacuum pumping port, if needed.
- Iterative RF-BeamDynamics-Thermal-Mechanical coupled optimization.

RF cavity types

Note: by definition, TE and TEM cannot accelerate beam if the wave propagating direction aligns with beam direction.

- Working mode:
  - TM-type RF cavities are widely used.
  - TEM-type RF cavities are also common.
  - -type means it is not strictly TM or TEM
  - Sometimes a cavity can be between TM-type and TEM-type
  - In some rare cases TE-type RF cavities are used.
- Lorentz force:
  - RF cavity that providing longitudinal (along the beam) kick is accelerating cavity
    - low-β cavity
    - high-β cavity
  - RF cavity that providing transverse kick is crab cavity (sometimes called deflecting cavity).

TM-type cavities

- Usually use TM_{010}–type mode in a cylindrical cavity (for example: a cylindrical cavity to accelerate the beam right after Tandem).
- It can be deformed to elliptical (for multipacting suppression, which will be introduced later), reentrant (higher Q, between TM-type and TEM-type), Quarter Wave Resonator (QWR, reduce the cavity size by bending the pillbox in radius, TEM-type).

Pillbox cavity

Elliptical Cavity

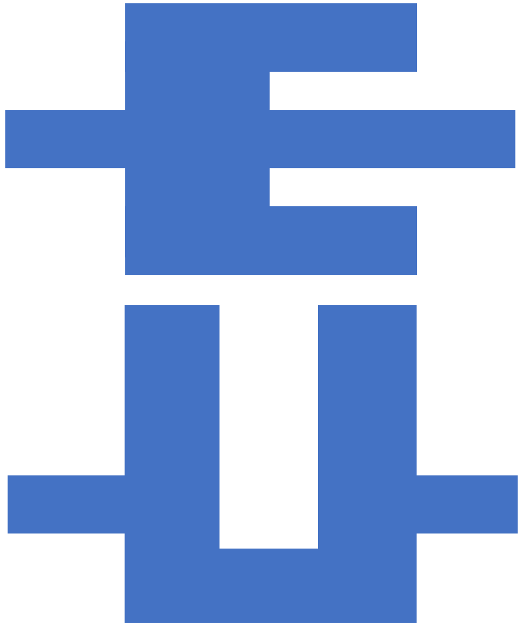
Pillbox cavity with nose cone (reentrant cavity)

Pillbox cavity bent in radius (when cavity is big at low freq)

TEM type cavities

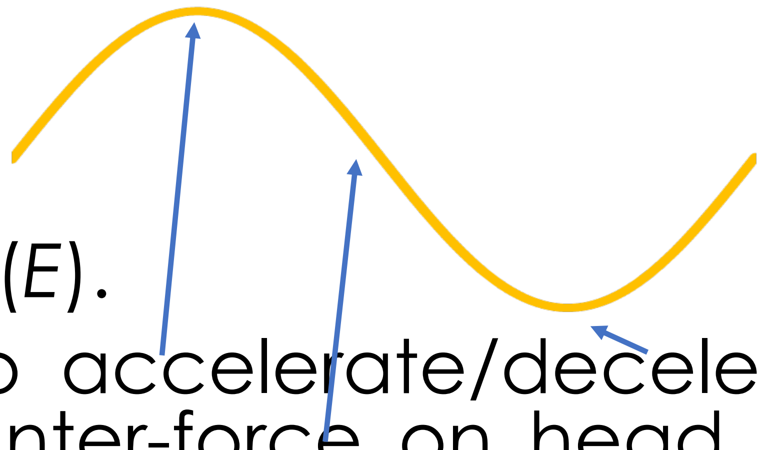
- Rectangular or circular waveguides/cavities do not support TEM. It needs to be Coaxial type.
- A natural choice is use HWR or QWR (accelerated by E_ρ), or QWR/DQW using E_z (virtual current along the broken inner conductor).
- The outer jacket of HWR can also be changed to form a Spoke cavity, which is easier to form multicell while comparing with HWR.

Half wave resonator



Quarter wave resonator

Accelerating cavities



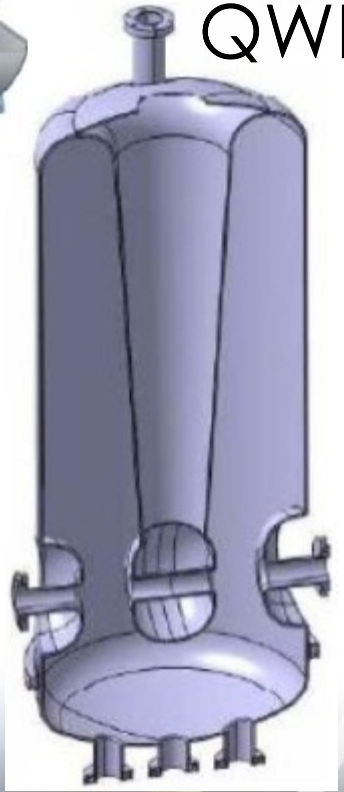
- Will show high-β cavity in detail later.
- Lorentz force in longitudinal direction (*E*).
- Accelerating cavity can be used to accelerate/decelerate beam, and sometimes provides counter-force on head and tail of the beam, with no effect to the center.
  - A majority of RF cavities are used to accelerate beam.
  - There are some RF cavities that are used in non-accelerating mode
    - in Energy Recovery Linac (ERL), accelerate and decelerate.
    - Can be used to enhance the beam energy uniformity.
    - Can be used to split a bunch or merge bunches.

Low-β cavities

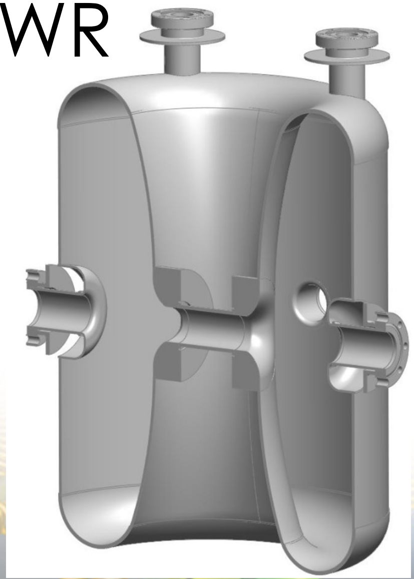
https://indico.cern.ch/event/626653/attachments/1524529/2383303/03_-_Non-elliptical_cavities.pdf

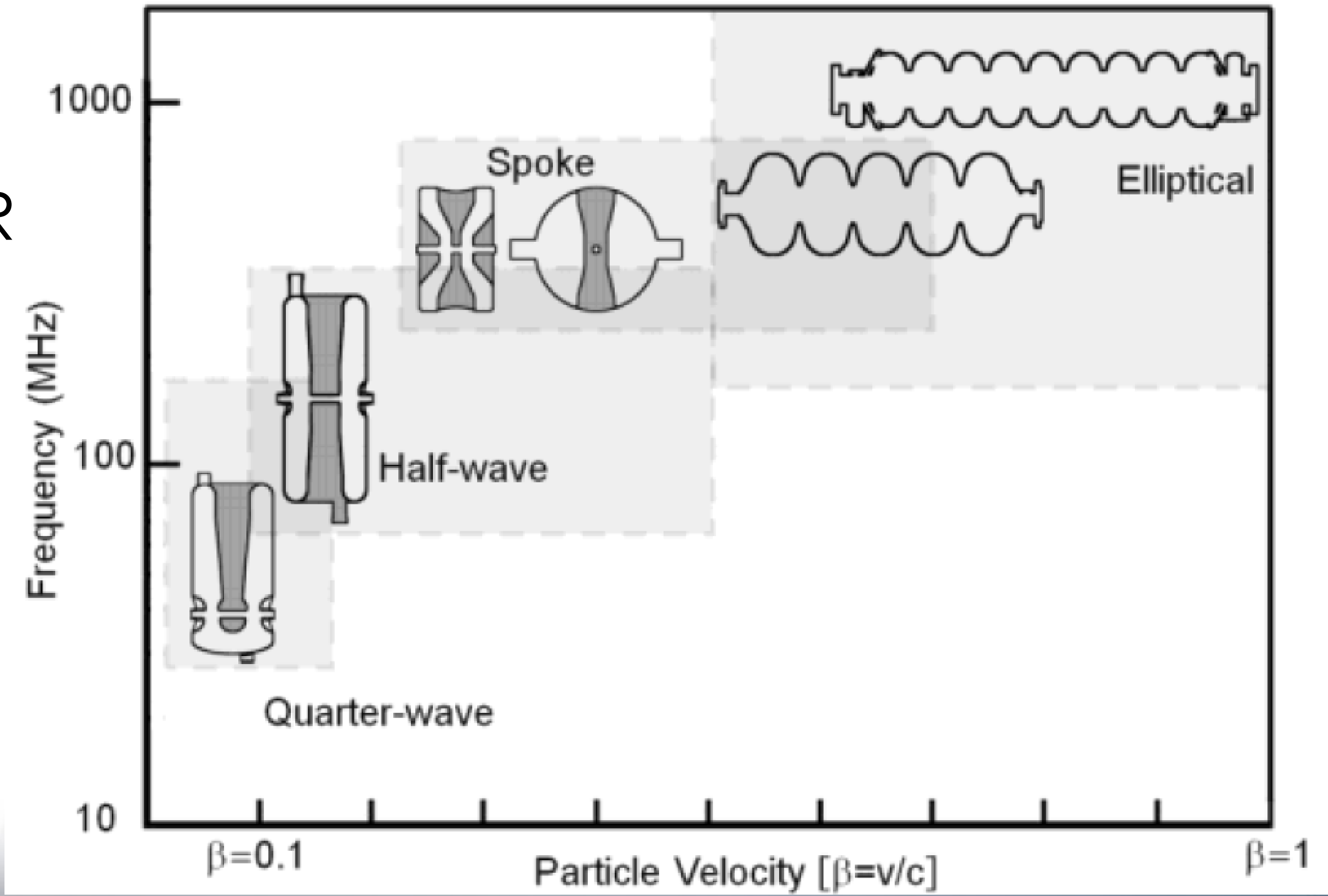
Spoke

QWR



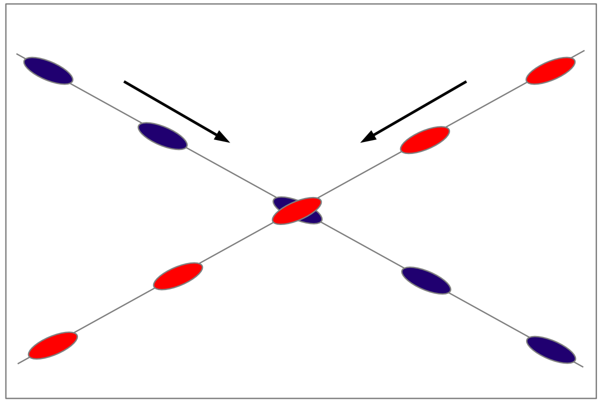
HWR



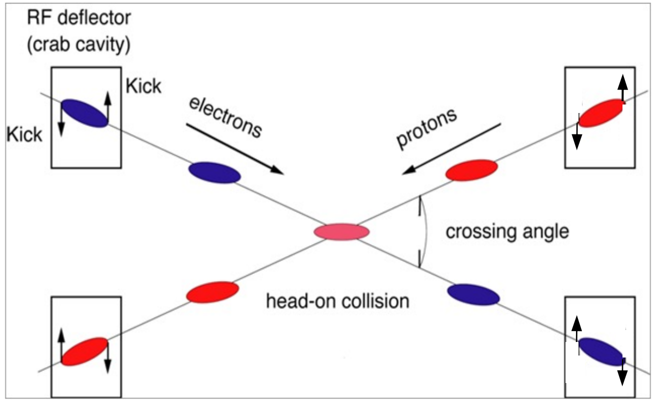


Crab/deflecting cavities

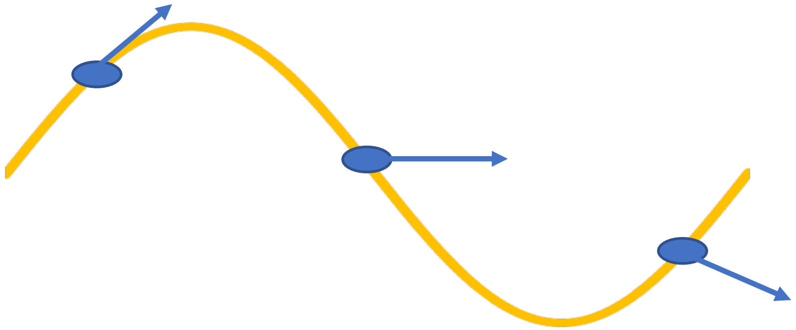
- Lorentz force in transverse direction (*E* and *M*).
- Crab/deflecting cavity can be used to tilt the head and tail of the beam, it can also be used to kick bunches to different angles (deflecting).



No crabbing



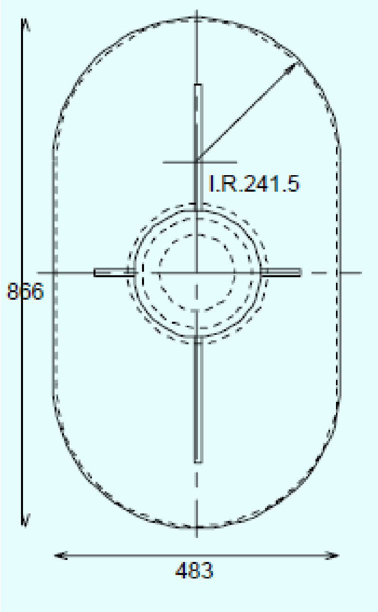
Crabbing and uncrabbing

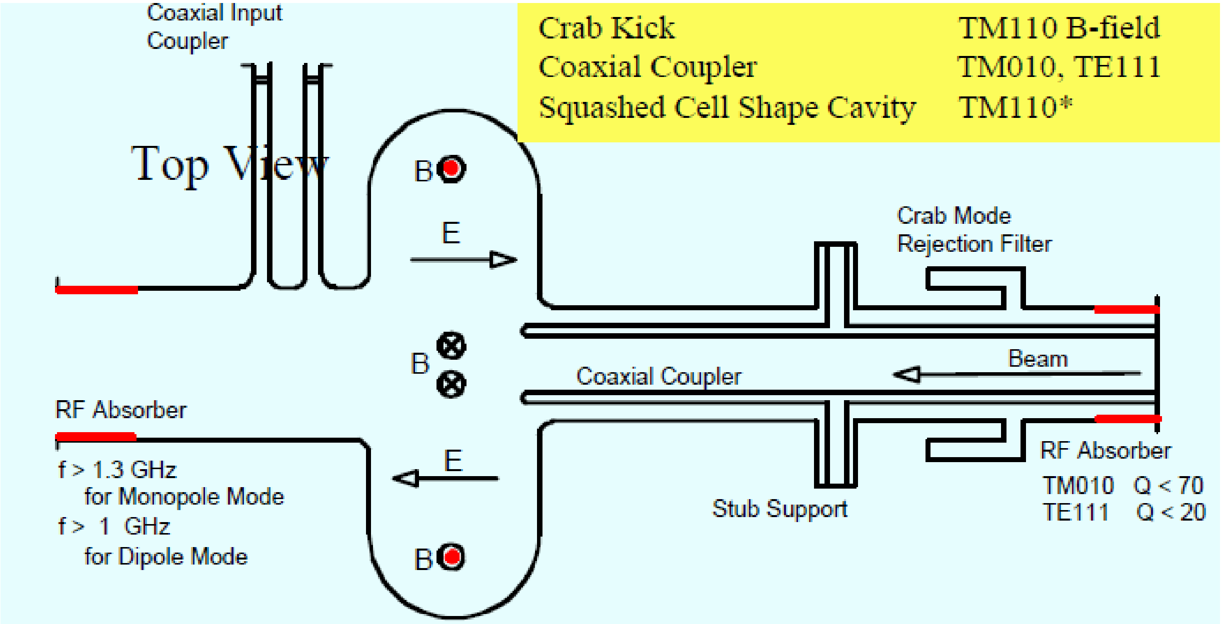


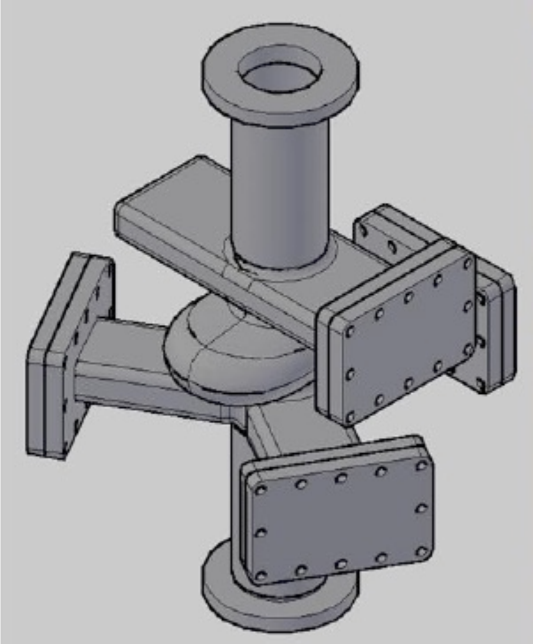
Deflecting

Crab/deflecting cavities

- KEK-B & ANL APS crab cavities, TM_{110} mode, different FPC and HOM damping designs



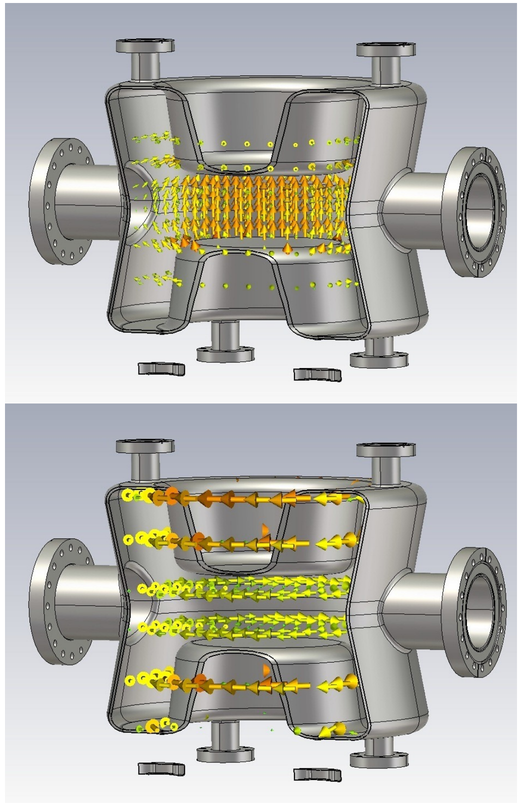


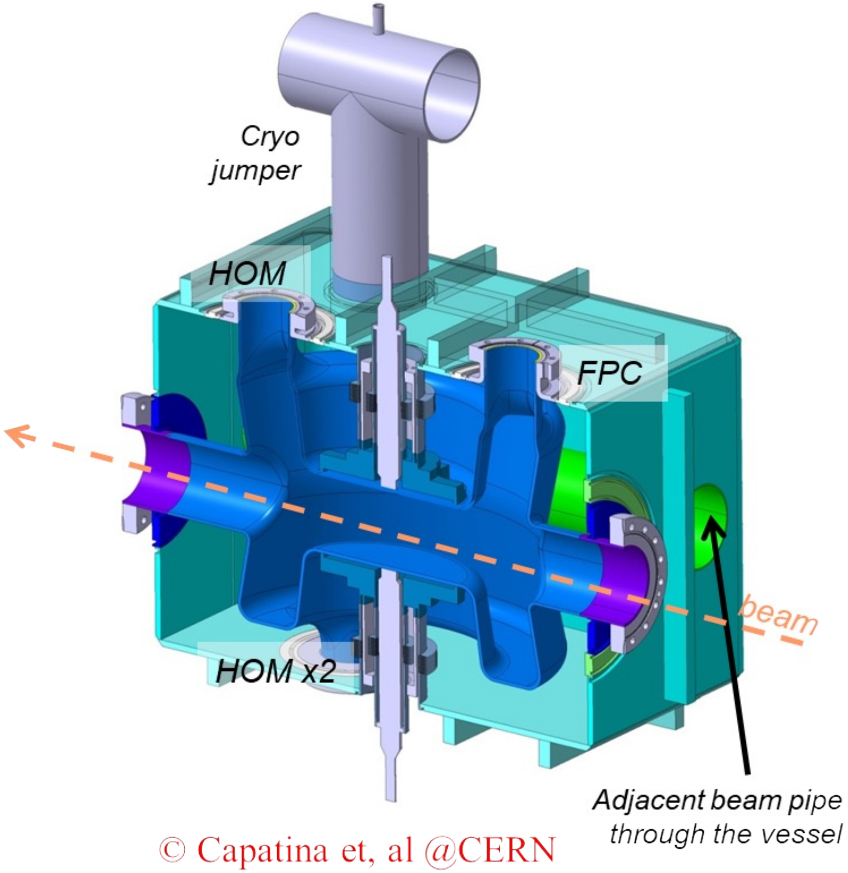


K.Hosoyama et, al. https://accelconf.web.cern.ch/e08/talks/thxm02_talk.pdf
H. Wang et, al. https://accelconf.web.cern.ch/IPAC10/papers/wepec079.pdf

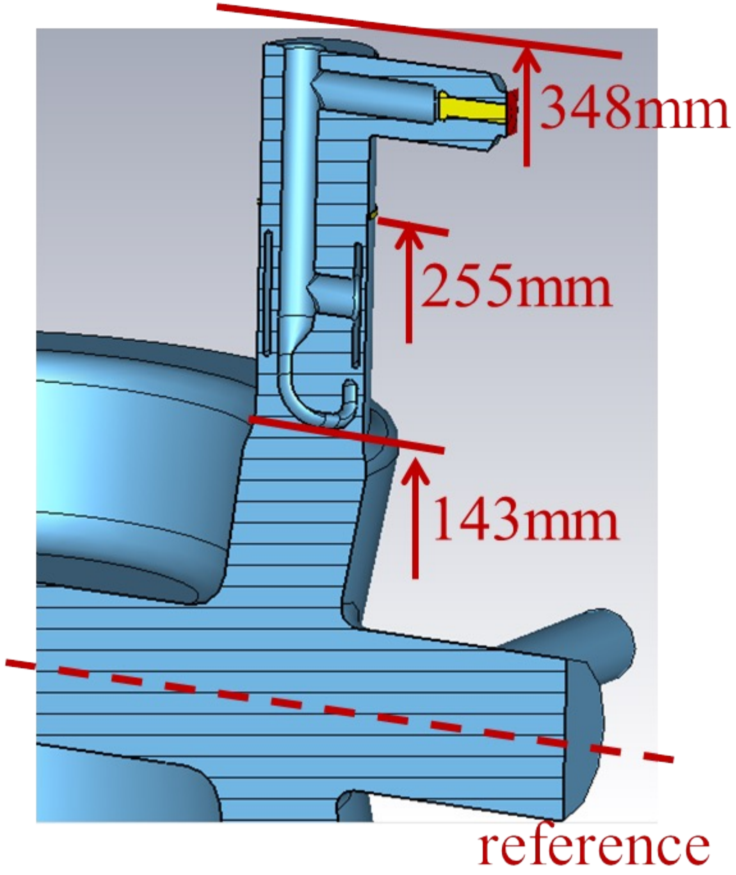
Crab/deflecting cavities

- BNL Double Quarter Wave (DQW) crab cavity for CERN LHC Hi-Lumi upgrade, TEM/TE/TM-like mode
- DQW is NOT HWR

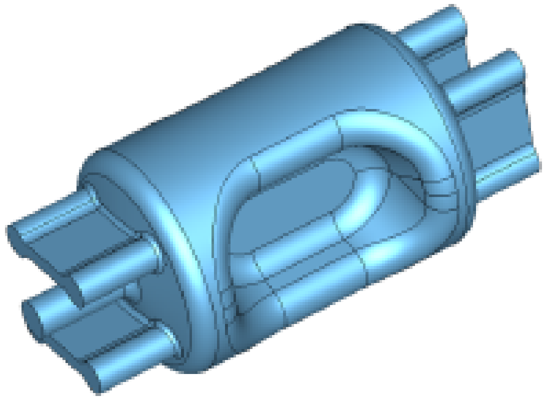




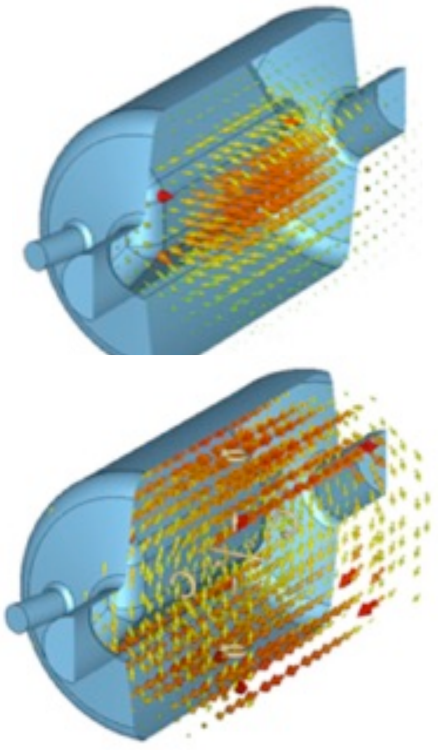
A liquid helium vessel for the HOM filter was not shown here

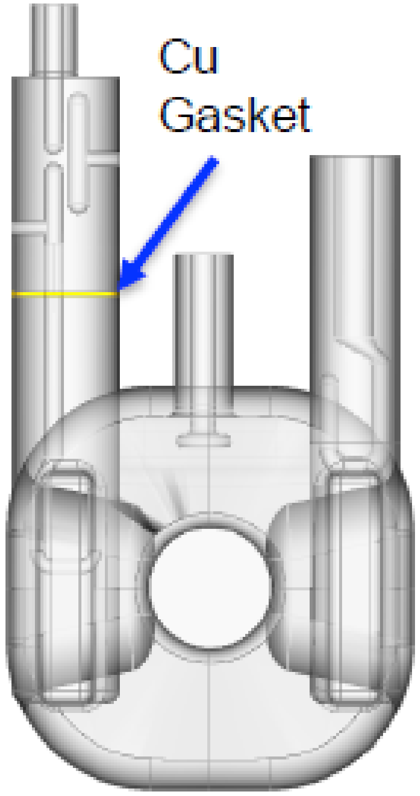


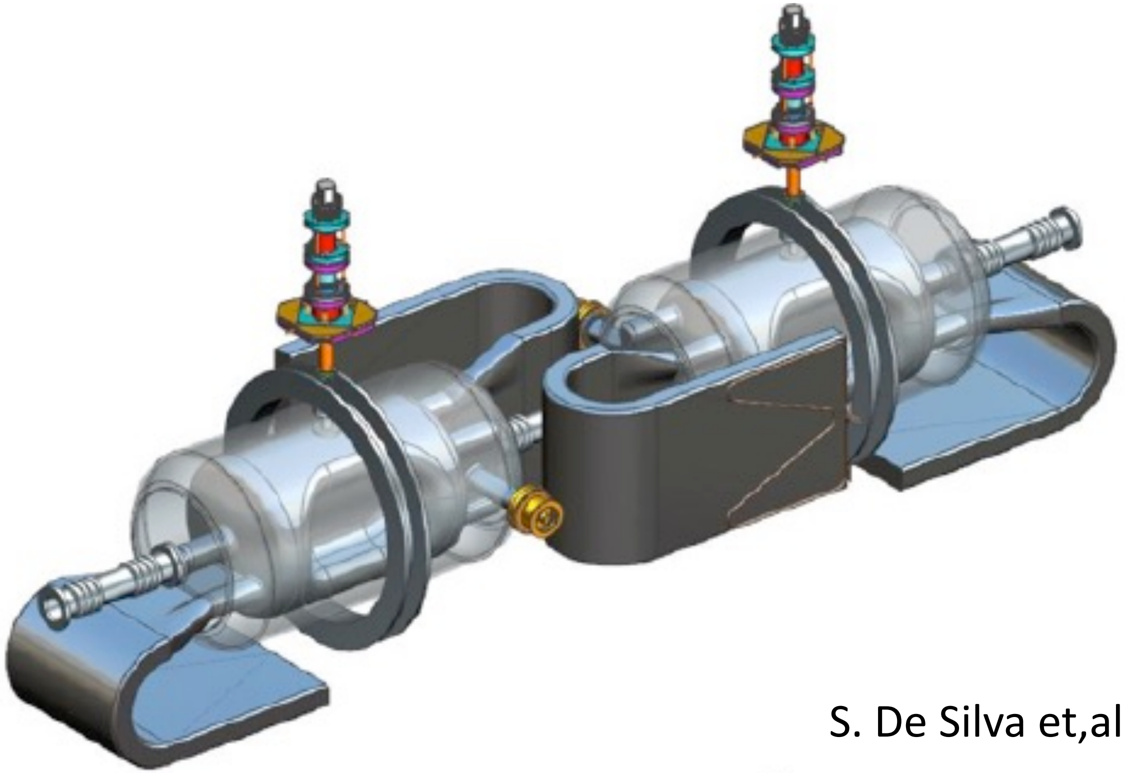
Crab/deflecting cavities



- RF dipole (RFD) crab cavities for LHC & EIC





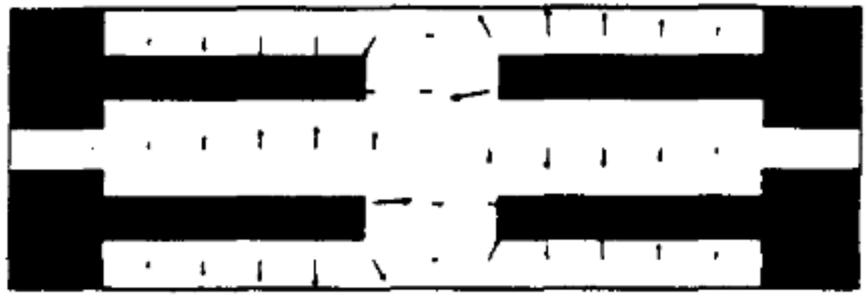


S. De Silva et,al.

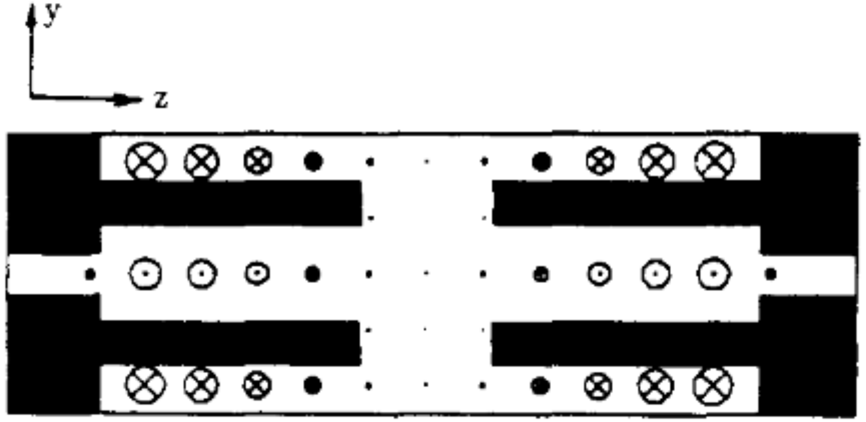
Crab/deflecting cavities

- 4-rod deflecting cavity at JLab to separate the beam

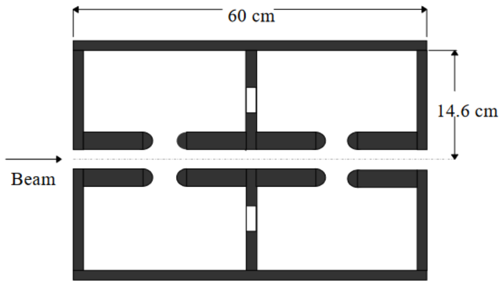
C. Leemann and C. G. Yao



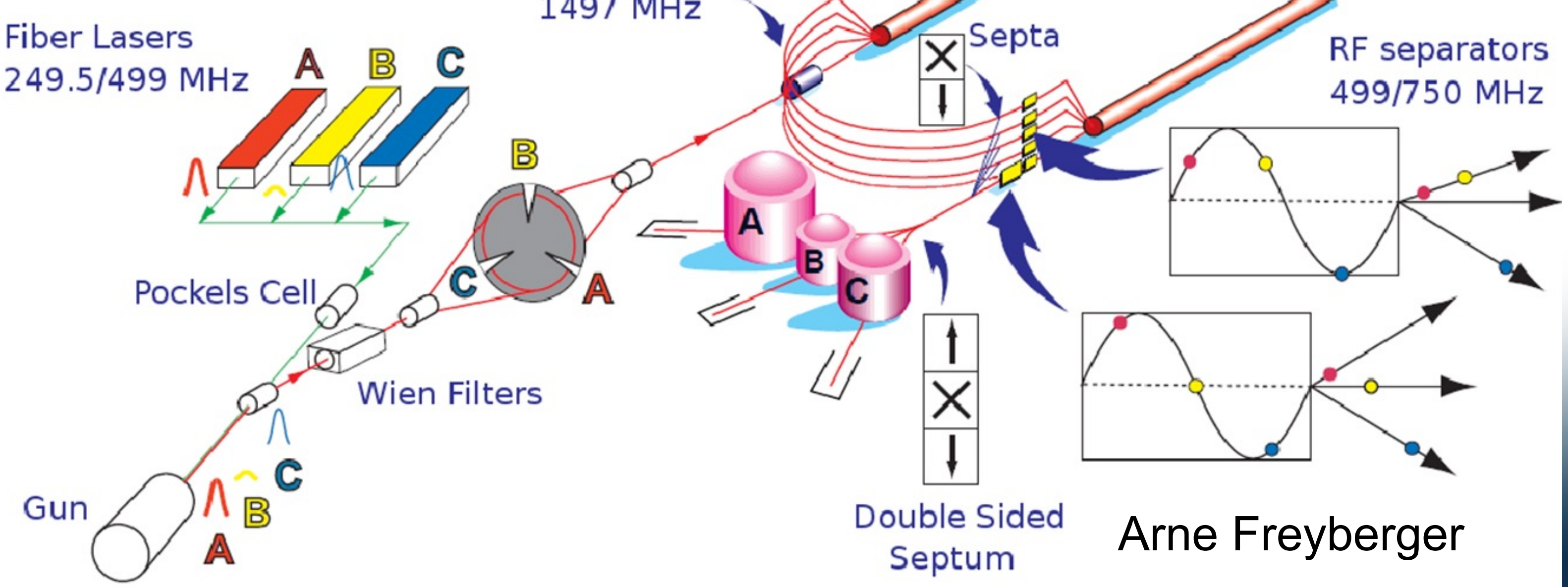
E field in y - z plane.



B field in y - z plane.



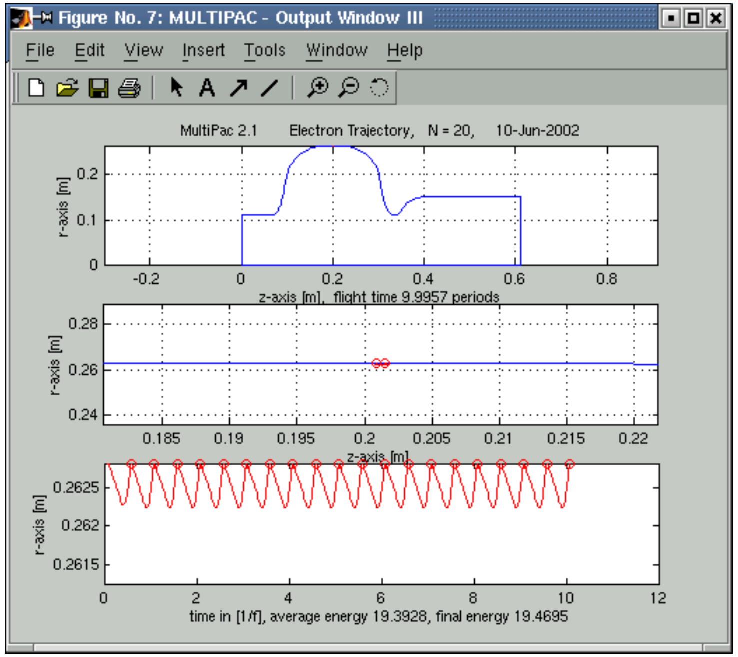
C. Hovater

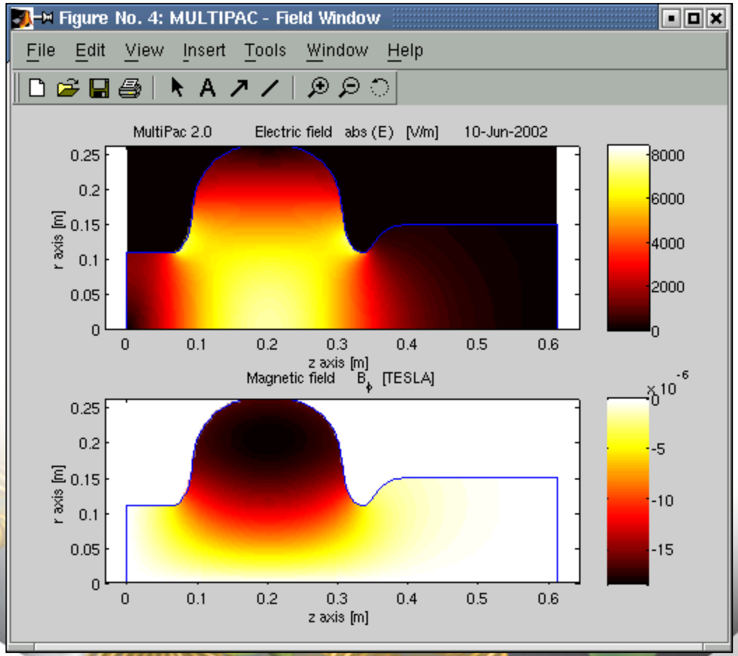


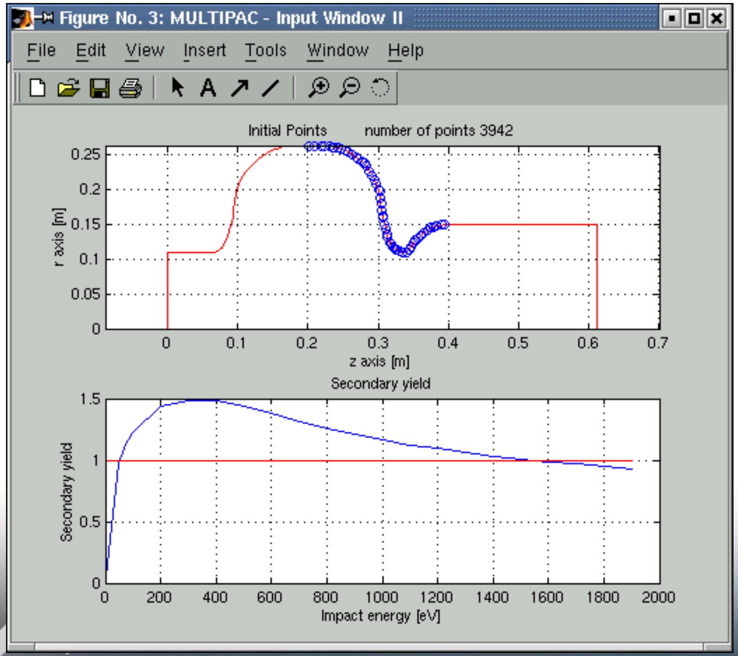
Arne Freyberger

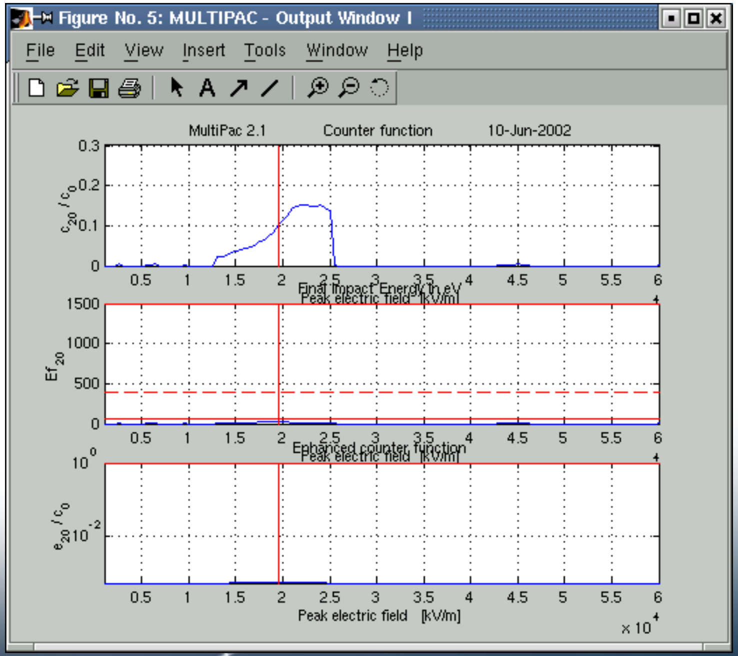
Multipacting

- Second electrons resonating/avalanching in the cavity that take power away and cause thermal quench.
- It was a major obstacle during the early age of SRF development, and it is still an issue that needs to be addressed now for a new design (cavity, especially low-β; coupler; RF window; transmission lines etc.)



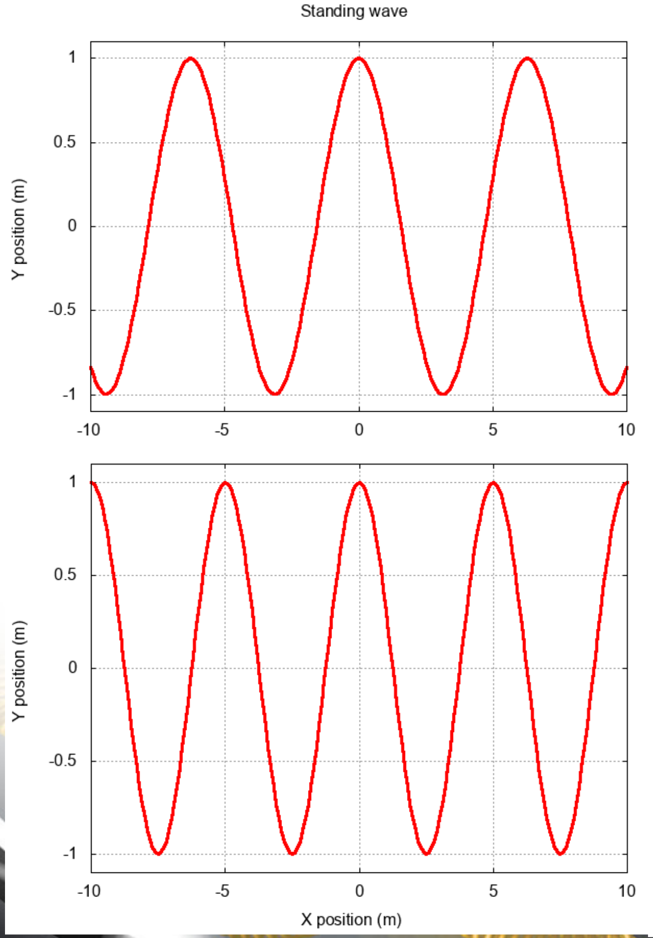




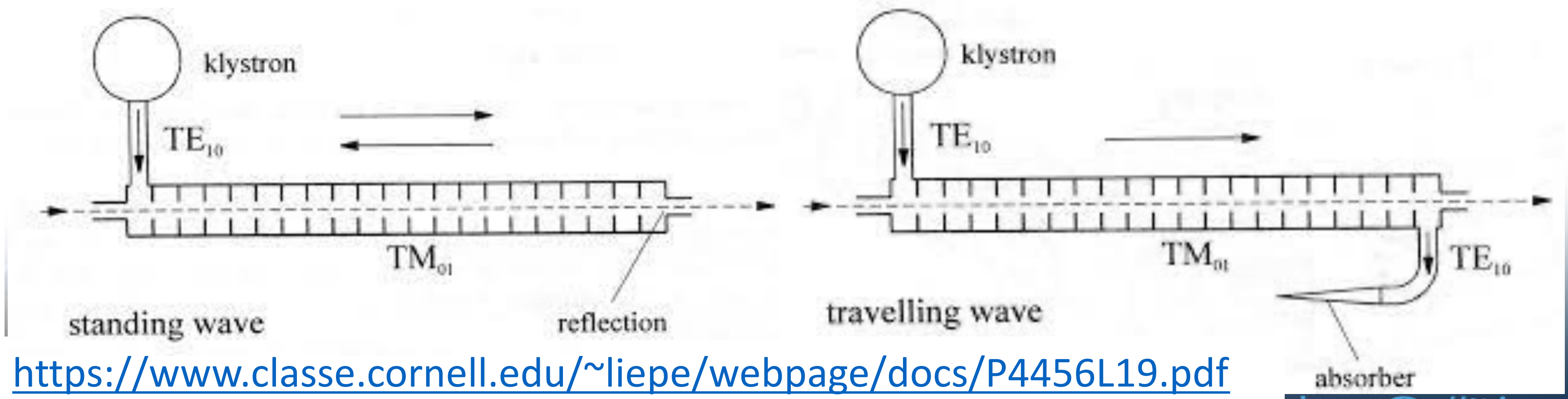


Traveling wave accelerator

http://spiff.rit.edu/classes/phys283/lectures/travel/travel.html



- Beam follows a peak of the wave → beam velocity equals to phase velocity.
- Phase velocity of rectangular/circular waveguides is higher than c, that of coax equals to c, they are not suitable.
- One needs to "slow down" the phase velocity. – One way is to put periodic disk on circular waveguide (disk loaded traveling wave cavity)

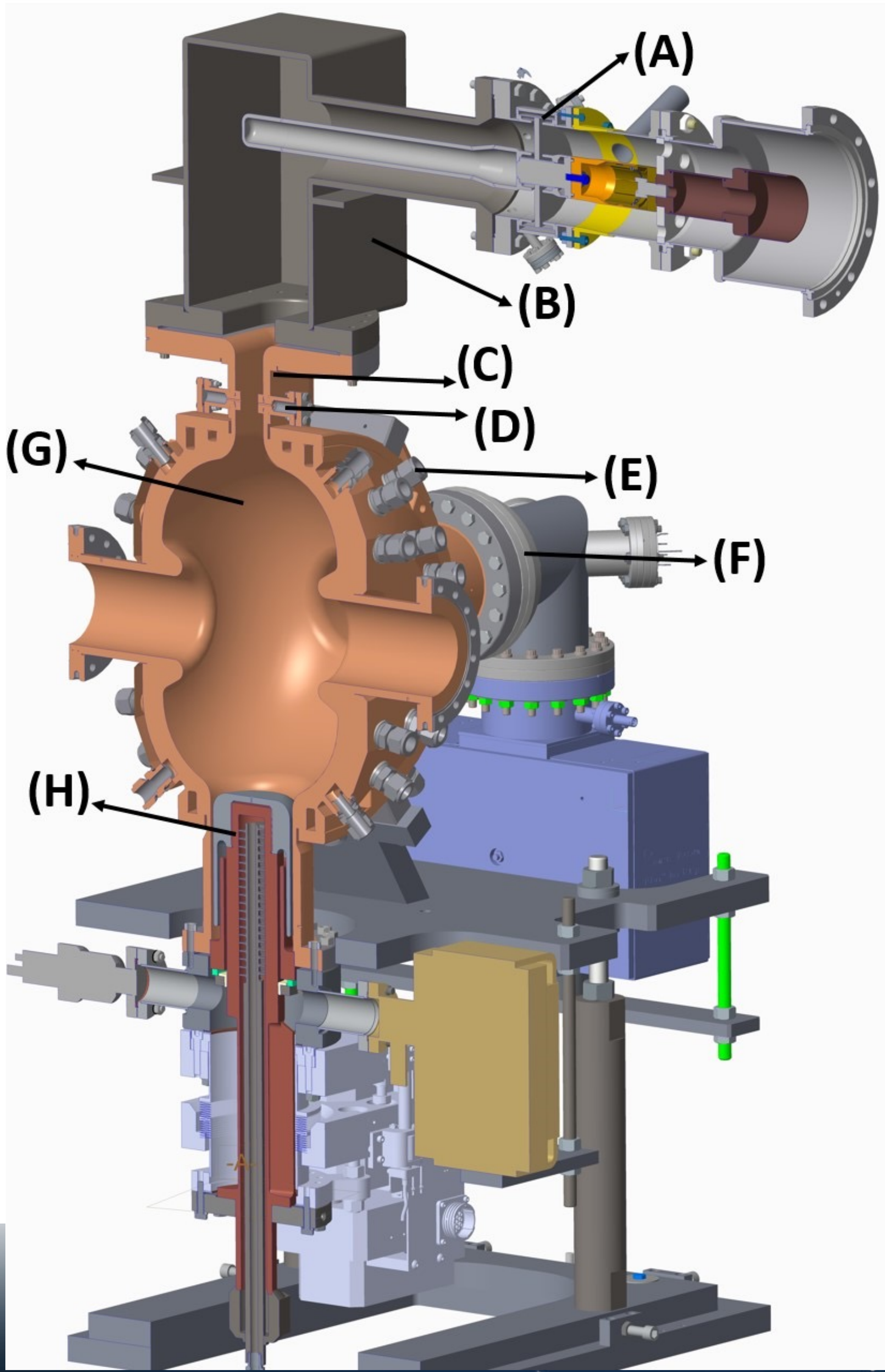


https://www.classe.cornell.edu/~liepe/webpage/docs/P4456L19.pdf

Some examples of TM_{010} cavities

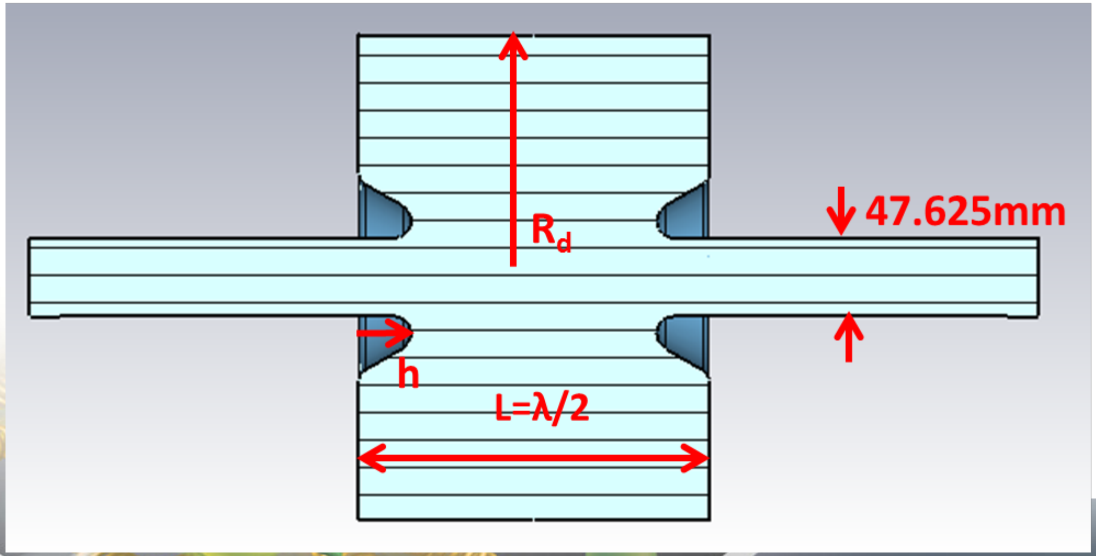
LEReC 704MHz cavity

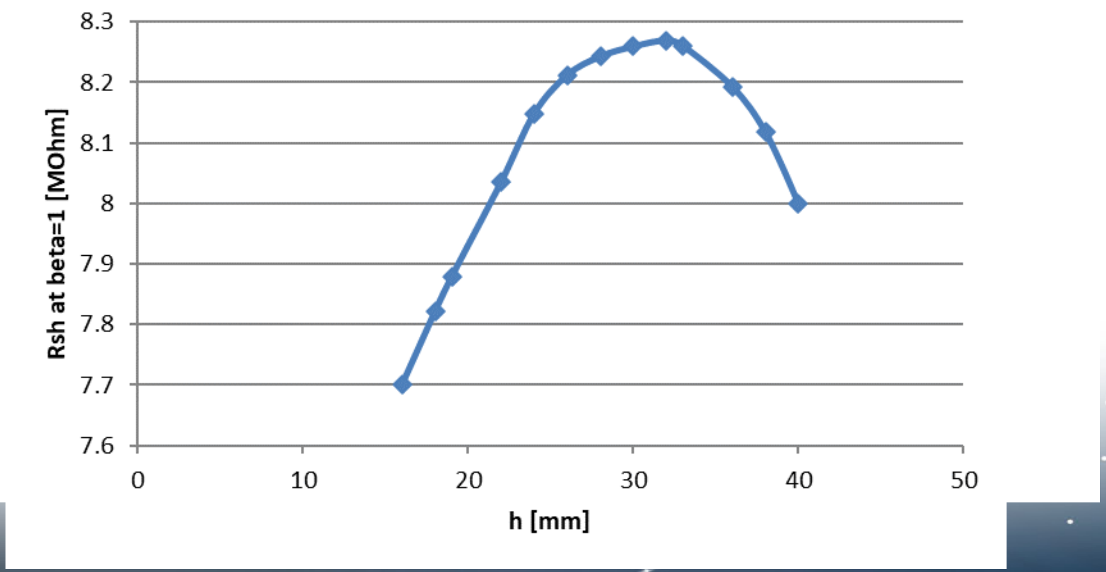
704 MHz cavity cross section view.
(A) Toshiba RF window;
(B) WR1150 waveguide to coaxial transition piece;
(C) FPC port;
(D) FPC tuner;
(E) cavity water cooling channel;
(F) vacuum pump;
(G) cavity body;
(H) main frequency tuner.



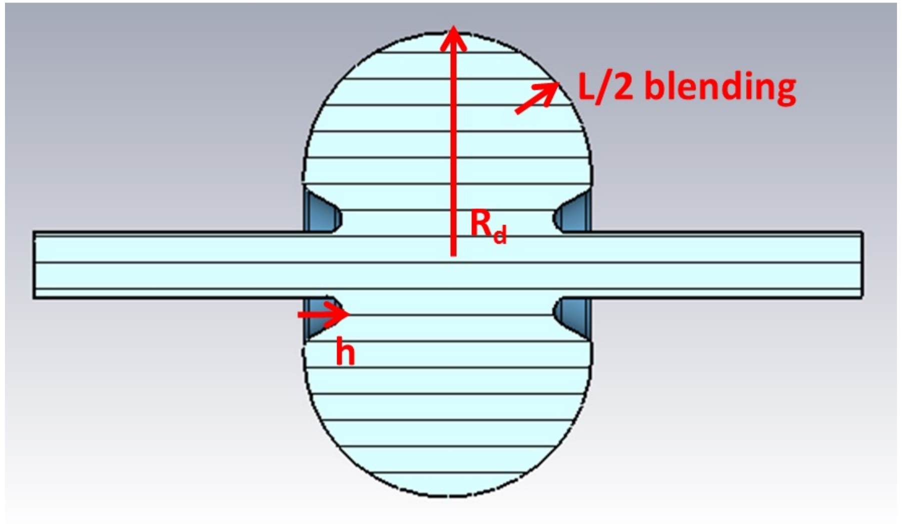
Cavity design: pillbox with nose cone

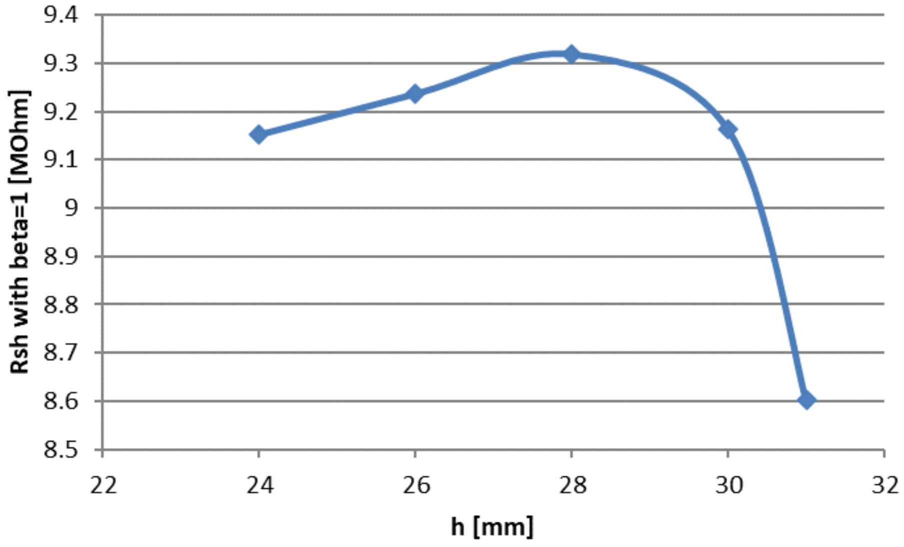
- Beampipe size is determined by the size of the beam (10σ)
- Cavity is half wavelength long
- For different h, Rd is optimized so that cavity frequency is 704MHz

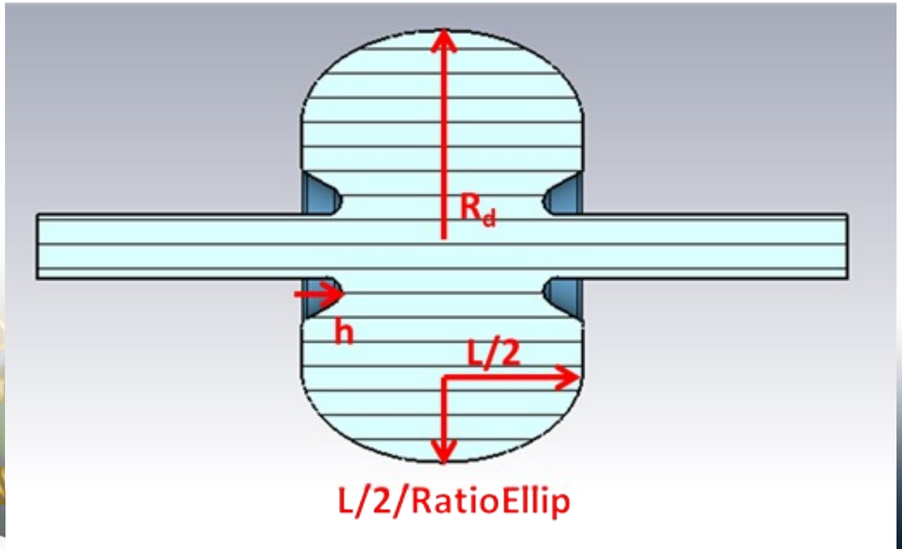


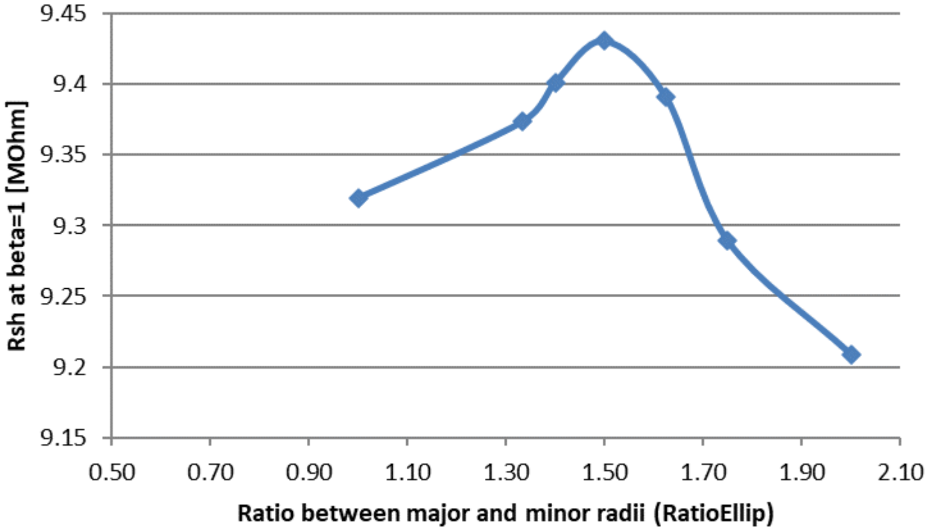


Cavity design: other shapes



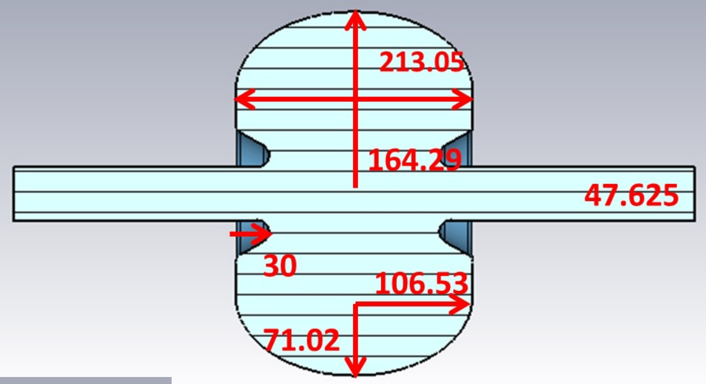


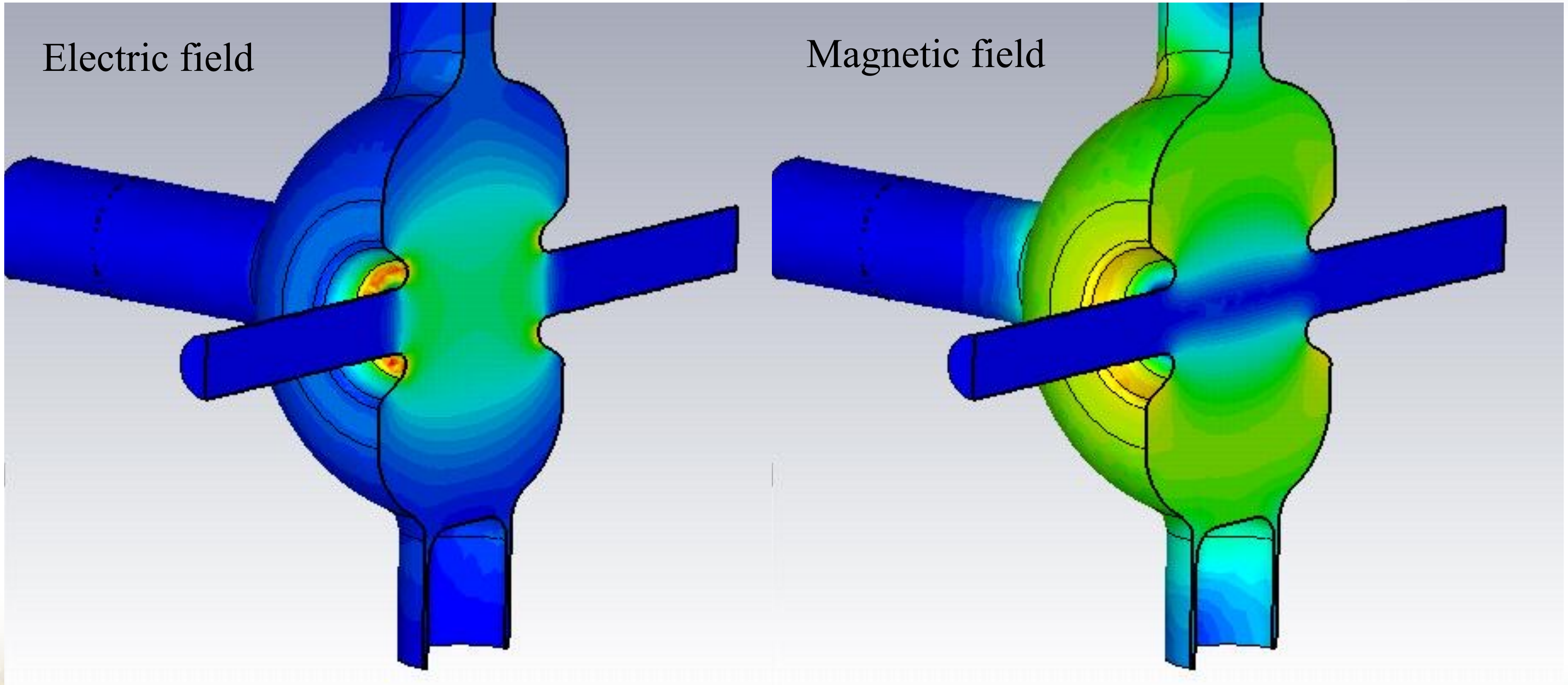




der

Cavity design: cavity shape

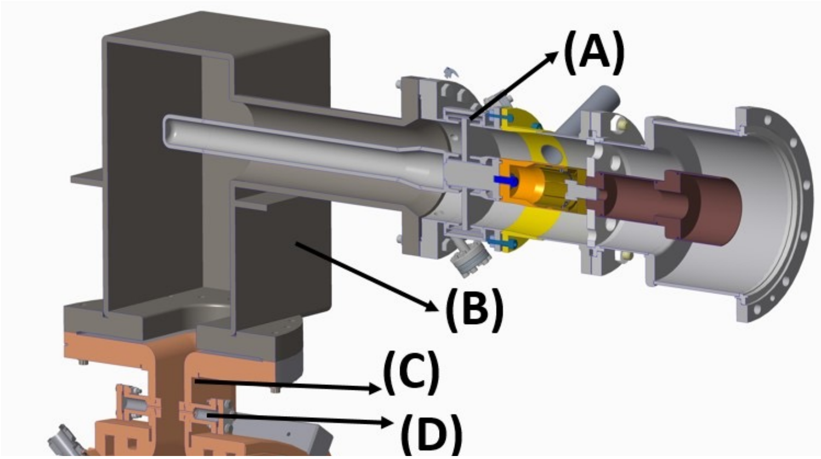




For 430 kV:
Peak electric field 8.1 MV/m, Peak magnetic field 9.4 mT

FPC

- TEM in coax to TE_{10} in rectangular waveguide
- Slot coupling to the cavity, with two knobs to adjust the coupling coefficient
- FPC over-coupled, with FPC Qext at 14,000 and cavity Q0 at 34,000
- 65kW amplifier
- Designed to provide 430 kV, with 35.5 kW power dissipation on cavity walls
- Operates at 250kV, with 9.5kW power dissipation on cavity walls

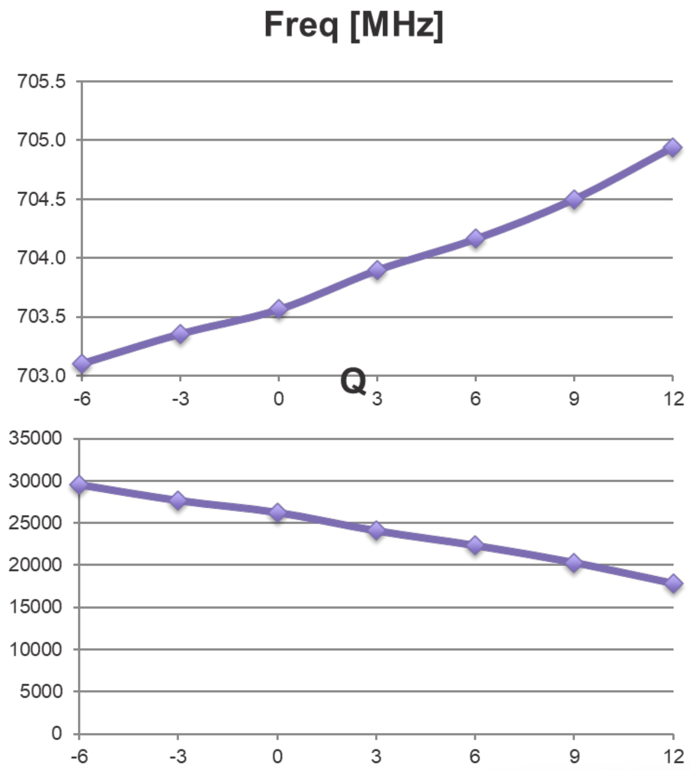


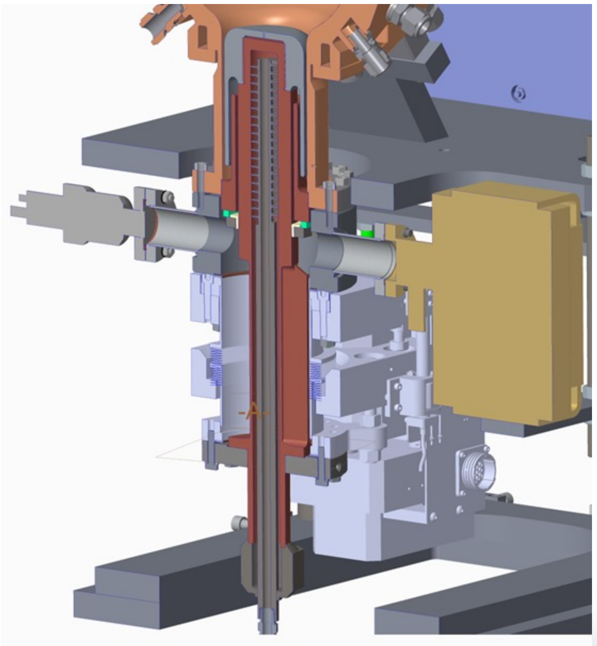
Tuner

- Folded coaxial design
- Fundamental mode matches to TE_{11} but not TEM
- Cutoff of TE_{11} much higher than 704MHz.

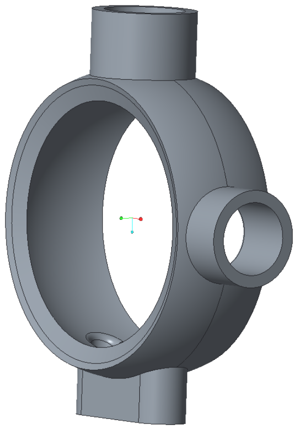
With L_t changes from -6mm to 12mm:

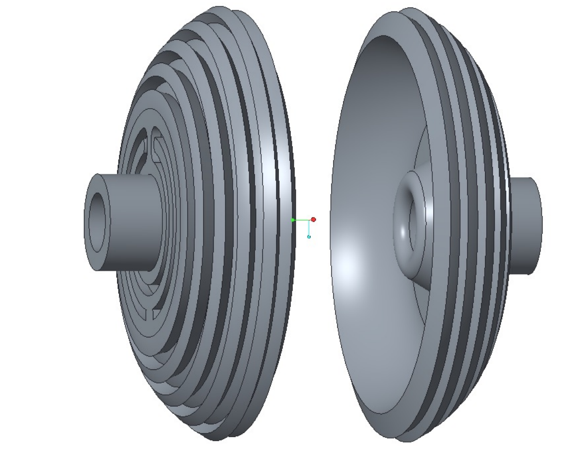
- R/Q decreases 1%
- Q_0 decreases 3.5%
- Frequency changes 2MHz

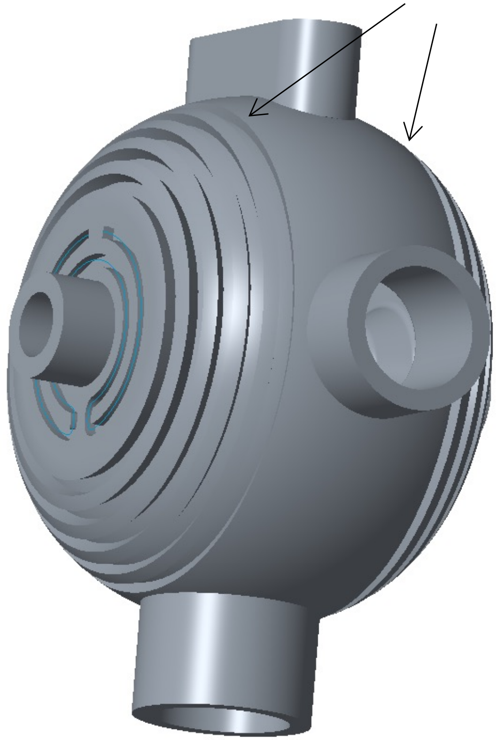


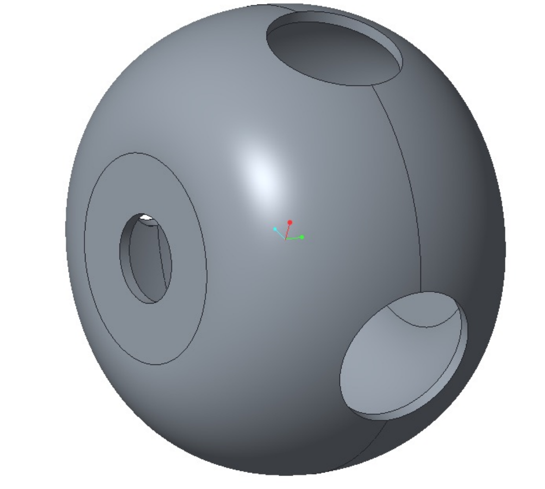


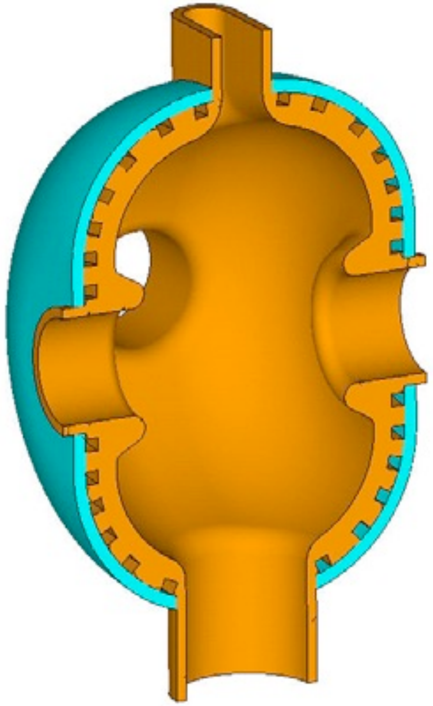
Cooling

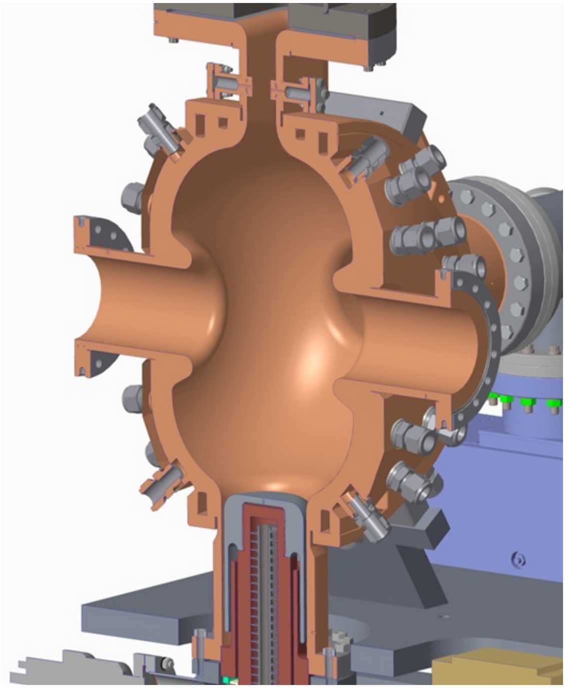






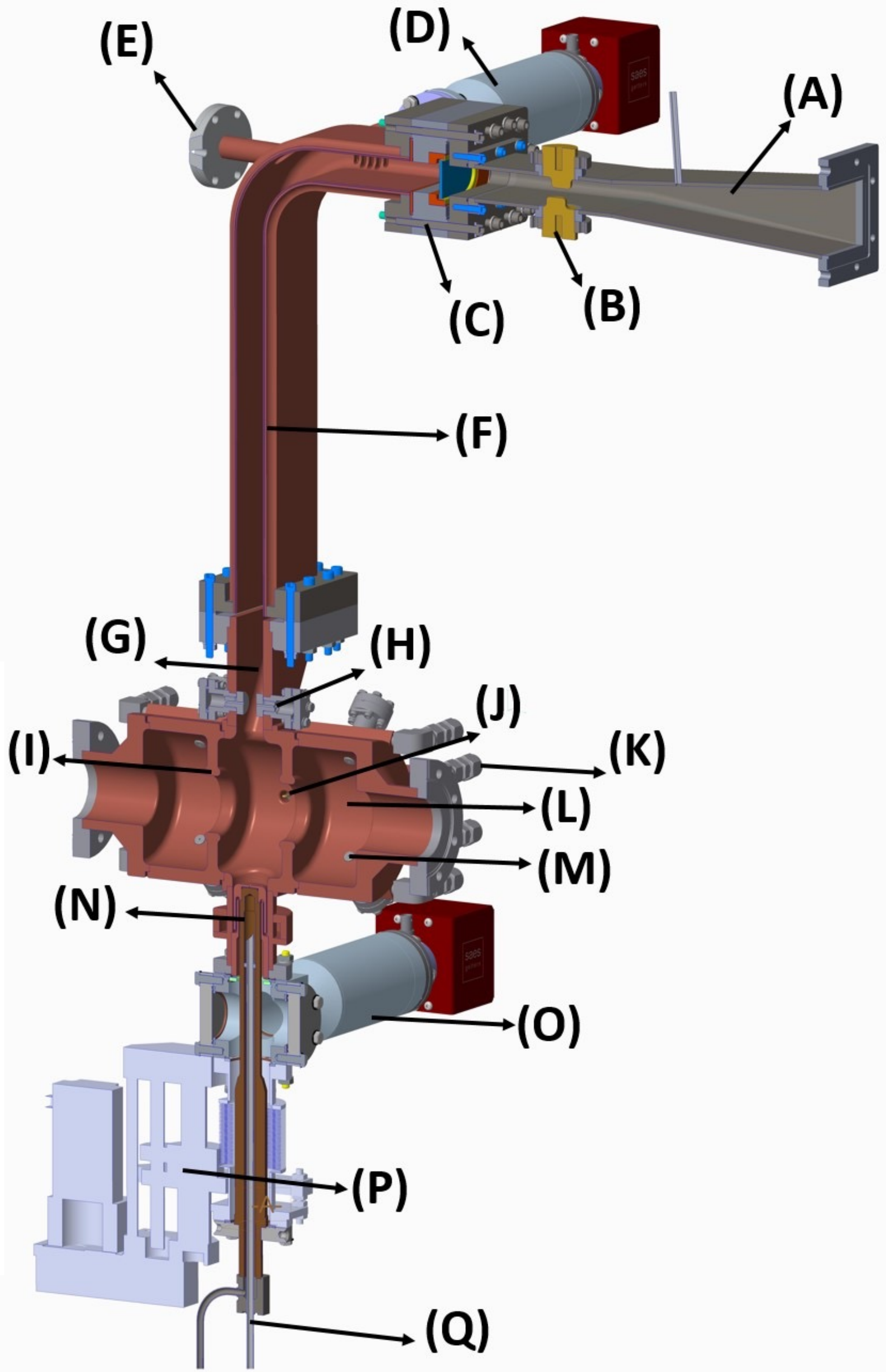




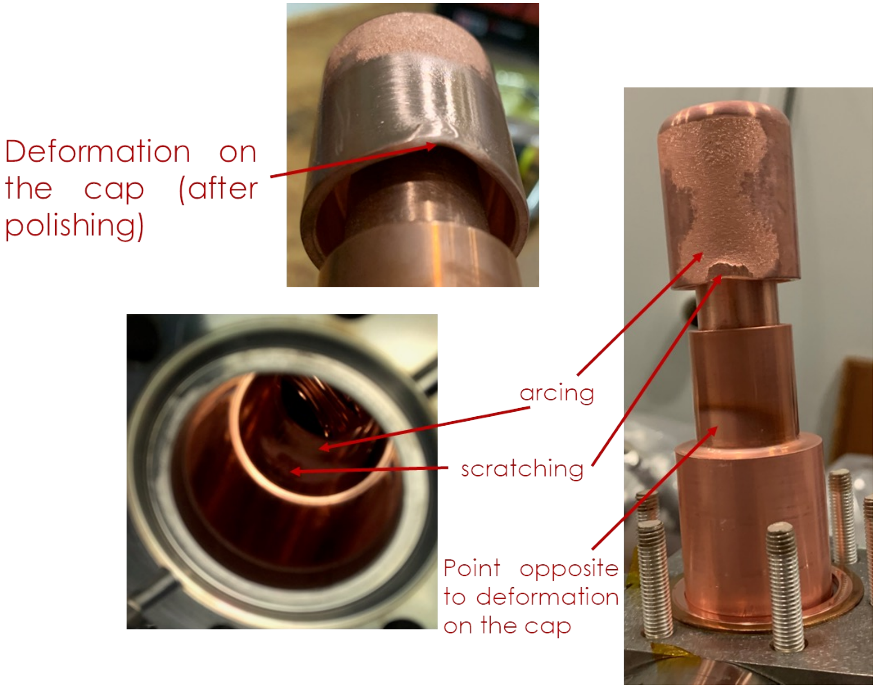


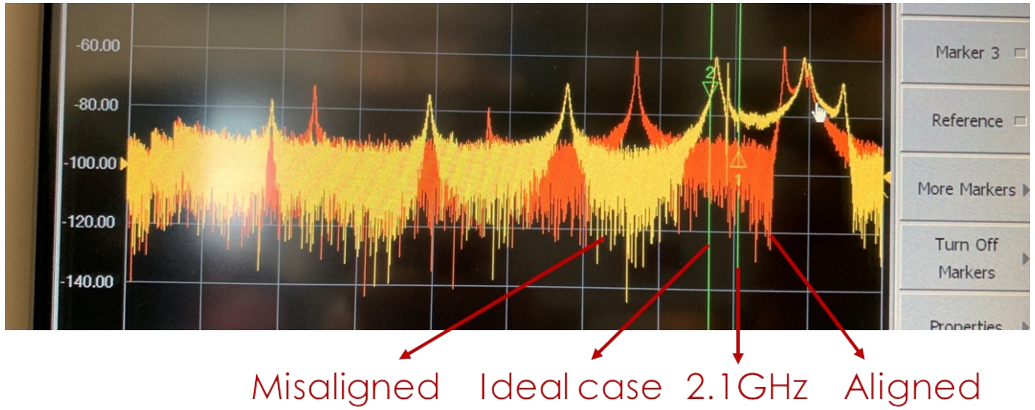
LEReC 2.1GHz cavity

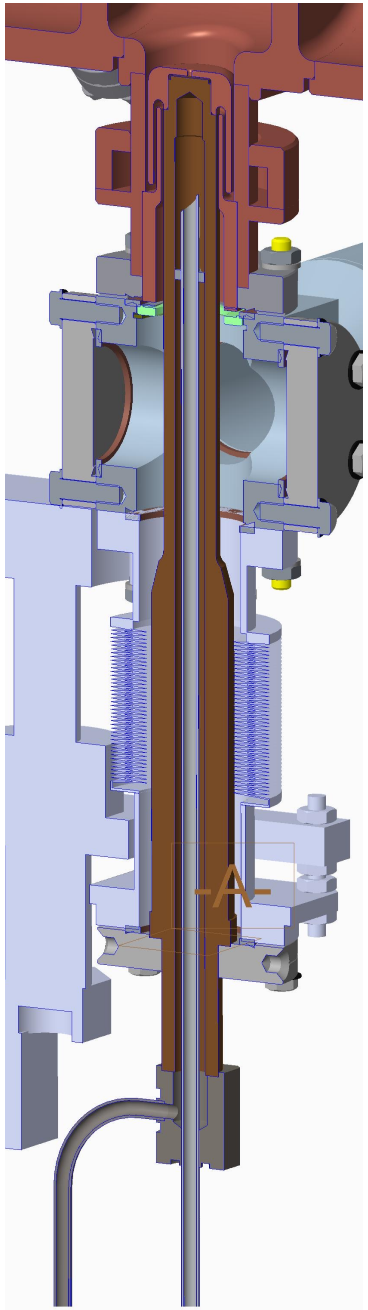
2.1 GHz cavity cross section view.
(A) waveguide adaptor from JLab530 to WR430;
(B) bolt with a non-concentric knob;
(C) JLab C100 RF window;
(D) vacuum pump near the RF window;
(E) view port;
(F) FPC waveguide;
(G) FPC port;
(H) FPC tuner;
(I) nose cone;
(J) pickup coupler;
(K) cavity water cooling channel;
(L) cavity body;
(M) fixed tuner;
(N) main frequency tuner;
(O) vacuum pump at the main tuner;
(P) driver for the main tuner;
(Q) main tuner water cooling channel.

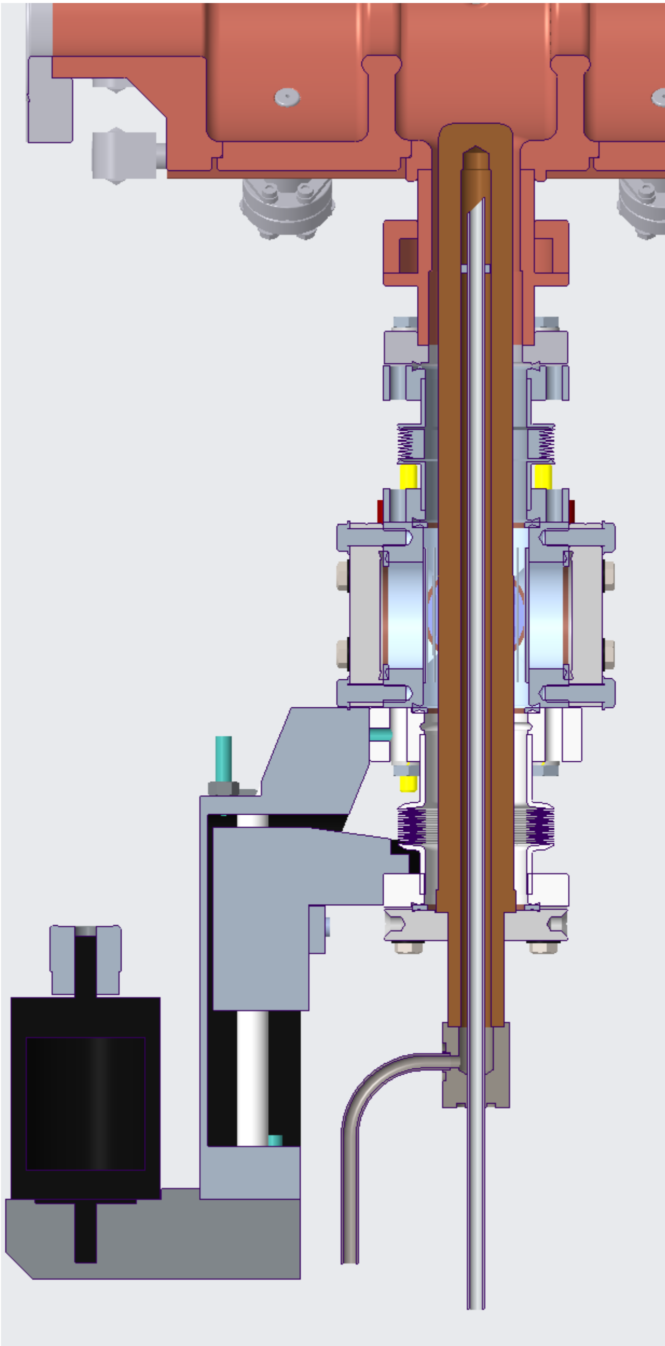


Tuner failure in 2.1GHz





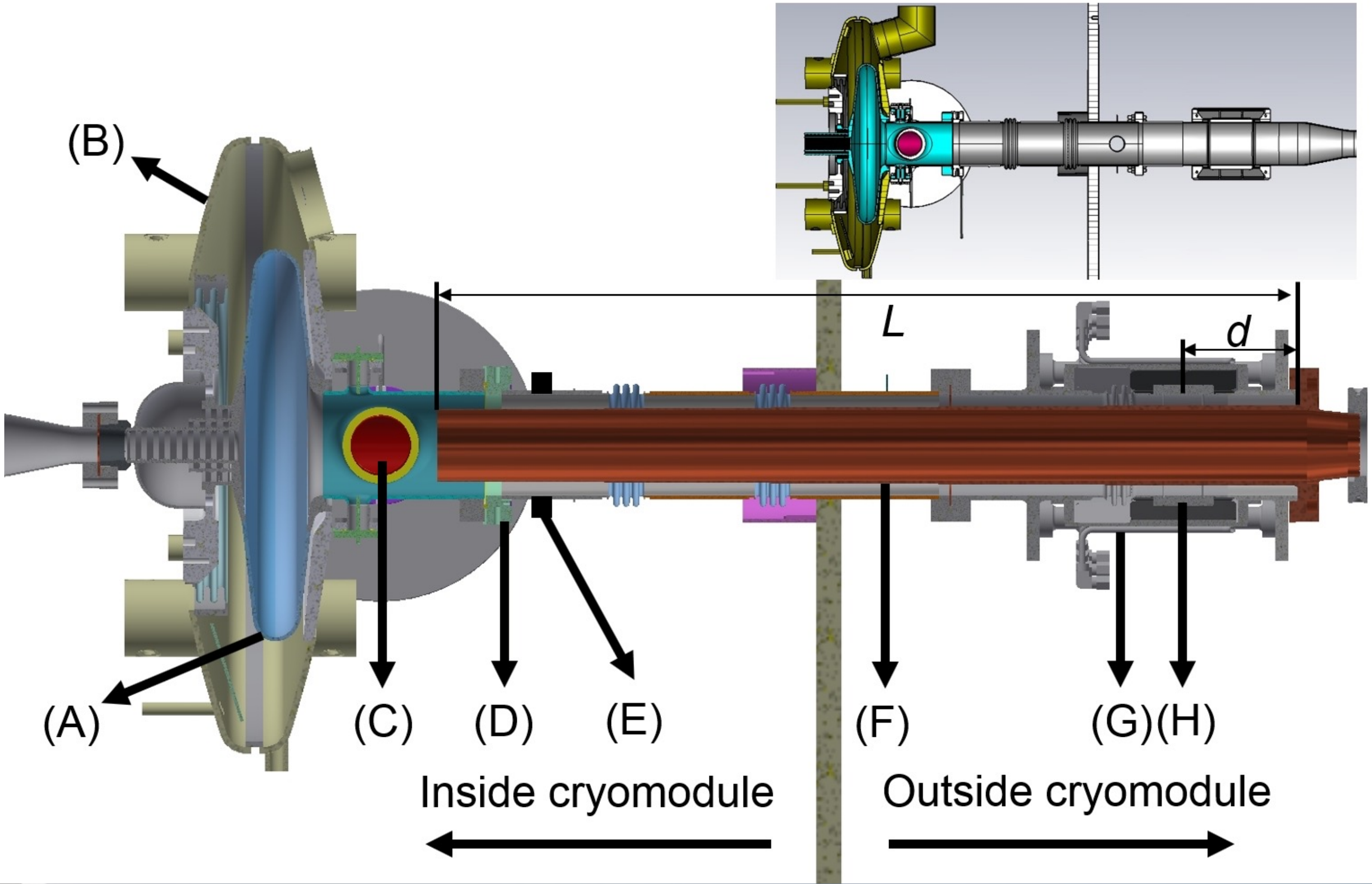




LEReC 704MHz SRF cavity

To minimize the damping to TM_{010}, $d \sim \lambda_{010}/4$, $L \sim m/2 * \lambda_{010}$.
To maximize the damping to TM_{020}, $d \sim \lambda_{020}/2$, $L \sim (n/2+1/4)\lambda_{020}$.

Booster cavity with new HOM assembly: (A) Nb cavity; (B) helium vessel; (C) two FPCs, with the other one opposite to the one shown in figure; (D) 5 K cold anchor; (E) 25 K cold anchor 1.3 cm width ring; (F) Cu tube for HOM damper, with *L* its length from the tip to the electric short on the right side; (G) HOM absorber assembly; (H) HOM RF window assembly, with *d* the distance between its centre and the electric short of Cu tube; Insertion on the top right corner: ERL photocathode gun with old HOM assembly.



- There are still a lot (scientifical/engineering/technical) that are not covered: amplifier, control, vibration, surface treatment, quality control during fabrication and assembly, installation/alignment, and (specifically for SRF) microphonics, Lorentz force detuning, cryogenics, …